Studies of Ionospheric Irregularities: Origins and Effects

Paul M. Kintner
School of Electrical and Computer Engineering
302 Rhodes Hall, Cornell University
Ithaca, NY 14853
phone: (607) 255-5304 fax: (607) 255-6236 email: paul@ece.cornell.edu

Michael C. Kelley
School of Electrical and Computer Engineering
318 Rhodes Hall, Cornell University
Ithaca, NY 14853
phone: (607) 255-7425 fax: (607) 255-6236 email: mikek@ece.cornell.edu

Award Number: N00014-92-J-1822
http://www.ece.cornell.edu/~spp/gps/gps.html

LONG-TERM GOALS

We have two long-term goals. The first goal is to understand the electrical properties of the upper atmosphere and space environment to better assist designers and users of space systems and technology. The second goal is to educate the next generation of leaders in space science and engineering.

OBJECTIVES

The scientific objectives of the project are to:

(1) Develop GPS receivers for measuring scintillations and scintillation effects on GPS signals and receivers;

(2) Investigate the effects of equatorial scintillation storms on GPS through field campaigns and deployment of GPS scintillation receivers at collaborating institutions in South America and globally;

(3) Investigate the effects of mid-latitude scintillation storms on GPS through the deployment of receivers at Puerto Rico, Hawaii, and Ithaca, NY;

(4) Develop space-based GPS receivers for sounding rocket and satellite applications;

(5) Investigate the role of plasma waves in accelerating particles (transverse ion acceleration), in creating auroral ion outflows, and in providing a mass source for the magnetosphere;

(6) Investigate the role of electron phase space holes in particle acceleration and thermalization of space plasmas.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Studies of Ionospheric Irregularities: Origins and Effects**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **School of Electrical and Computer Engineering,,302 Rhodes Hall, Cornell University,,Ithaca,,NY, 14853**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We have two long-term goals. The first goal is to understand the electrical properties of the upper atmosphere and space environment to better assist designers and users of space systems and technology. The second goal is to educate the next generation of leaders in space science and engineering.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Our research focuses on the study of waves, irregularities, and wave-particle interactions in space plasmas as well as the effects of these processes on radio signals and energetic plasmas. Our approach is primarily experimental, and we have a reputation for producing cutting edge instrumentation and developing successful experiments. The vast majority of the universe exists in a plasma state and we focus on our own upper atmosphere and ionosphere as natural laboratories for studying space physics and as an environment that affects satellites and their signals. This yields a mix of applied and curiosity-driven research. By primarily employing sounding rockets and ground-based instrumentation, graduate students are able to participate in the full range of research and develop into future leaders. For example, our development of multiple-sensor plasma wave interferometers, beginning with the Viking spacecraft and continuing with sounding rockets, is now a standard feature of ionospheric and magnetospheric missions. During the past several years we developed a GPS scintillation receiver that has been deployed at multiple sites across South America. This receiver not only monitors ionospheric scintillation but additionally measures ionospheric drifts. Furthermore, this effort is currently leveraging our development of space-based GPS receivers.

APPROACH

Our scientific strategy emphasizes experimental development. We have chosen this route because the field of space science, especially the electrical properties of space, is still experimentally limited. Theories of space physics and space plasma physics are quite plentiful, but discriminating measurements are few and far between. Within this context one may well ask what areas need the most attention. The answer concerns nonlinear problems involving plasma waves and electric fields in collisionless environments and turbulent media. Incidentally, these areas are also examples that, at one extreme, can test theories of basic plasma physics and, at the other extreme, are important for the development and application of new communication and navigation technologies.

The logistics and operational challenges of ground-based experimentation are relatively new developments in our experimental program since most of our previous work was with space-based experiments. Since we lack the infrastructure to develop our own ground-based measurement program, we have created a new vision or “business plan” for obtaining ground-based measurements. We give GPS receivers away “free” to collaborators who then operate the receivers in regions of geophysical interest and share their data with us. This approach has been highly successful and we have established a regional chain of GPS scintillation receivers in South America (mostly Brazil) from the equatorial anomaly to the geomagnetic equator. Several receivers have also been placed with a colleague’s (Dr. Michael Kelley) instrument to optically observe the ionosphere in Hawaii and Puerto Rico. We are also extending our expertise in ground-based receivers to space flight. Three receivers were launched in a sounding rocket investigation of the northern lights this past January and we are working with a colleague (Dr. Mark Campbell) to create a GPS receiver for a CUBEsat project. This latter instrument will be used to sense ionospheric scintillations of GPS signals in orbit for the first time.

WORK COMPLETED

(1) Analyzed GPS equatorial scintillation data from a three-month campaign, employing five receivers on a 700 m by 1000 m grid, and demonstrated the speed, shape and duration of fades.

(2) Developed a Linux-based GPS scintillation receiver that operates over the web in real time. See, for example, http://gps.ece.cornell.edu/, where nightly scintillations in Brazil, Hawaii, Utah, and NY can be observed.

(3) Developed, fabricated and flew three sounding rocket “class” GPS receivers in an auroral sounding rocket experiment involving multiple payloads.

(4) Conducted a three-month joint radar-GPS receiver campaign at Sao Luis, Brazil on the magnetic equator to determine the altitude of the irregularities producing GPS scintillations.

(5) Demonstrated an orbital GPS scintillation receiver concept for CUBEsat.

(6) Continued analysis of Cluster wideband electric field data and identified the existence of electron phase space holes in the bow shock transition region.

RESULTS

From item (1): In the previous report year we conducted a special three-month campaign in Cachoeira Paulista, Brazil, under the equatorial anomaly, to understand and parameterize the spatial and temporal characteristics of GPS L1 scintillations. This campaign produced 100 GB of data which have been transferred to hard disk drives for analysis. The resulting data have been reduced to cross correlation coefficients among the five receivers which are amenable to analysis. From the cross correlation data we have investigated the spatial and temporal properties of amplitude fades. Note that this is a different approach from most research that has typically investigated scintillation climatology through the S4 index. That is, others have addressed the questions of when, where, and how much. On the other hand, we have investigated the questions of how fast, what shape, and for how long because these questions are important in understanding the potential effect of scintillation on moving GPS receivers.

Scintillations or fades can be thought of as a translating spatial pattern that is evolving in its own reference frame. Hence fades may appear to be quite different in the reference frame of a moving receiver. First we investigated the velocity of the fades. Using three GPS receivers aligned in the east-west direction with up to 715 m separation, we demonstrated that fades typically move toward the east at 100-200 m/s although higher velocities are observed earlier in the evening.

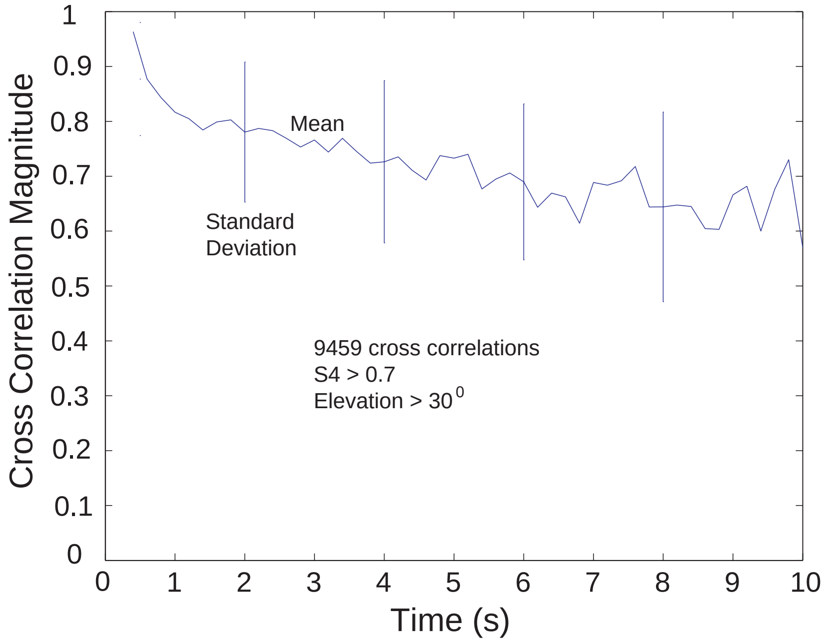

Figure 1. The mean value of cross-correlation amplitudes as a function of time in the moving reference frame. The distribution is created with 9459 cross correlations of 40 s length and from satellites with S4> 0.7 and elevations greater than 30°.

Next we determined fade time scales that resonant GPS receivers would observe. Figure 1 shows the decay of the cross-correlation magnitude with time and the "error bars" represent one-sigma variations of real statistical variation. Hence after 10 seconds one would expect a significant fraction of the fades to have a cross-correlation magnitude of greater than 0.8, implying that they are essentially unchanged. We conclude from Figure 1 that the time scale for significant fade amplitude decay is about 10 s.

Other results from item (1) have demonstrated that the fades are greatly elongated in the north-south direction and that they are tilted depending on the magnetic declination and the satellite elevation and azimuth. The consequence of these results is that scintillation fades can be much more problematic for moving receivers than for stationary receivers, and for safety-of-life applications these results must be considered carefully.

From item (2): We developed remotely operating GPS scintillation receivers that are accessible over the web. We are now accumulating scintillation data in the more traditional climatology approach but for the first time at mid-latitudes. Figure 2 demonstrates an example of scintillations at Hawaii. Note that this latitude maps to above the spread-F equatorial ionosphere.

A similar receiver operating in Ithaca, NY observed GPS scintillations adequate to cause loss of lock. Figure 3 shows an example of these fades which occurred during a modest magnetic storm on September 25-26, 2001 (*Ledvina et al.*, 2002). In this example a large ionospheric density surge, sometimes call a storm-enhanced density event, moved up the east coast of the US, encountering the subauroral ion trough. The encounter resulted in steep density gradients (not shown) and large amplitude scintillations, large enough to produce the loss of tracking shown in Figure 3.

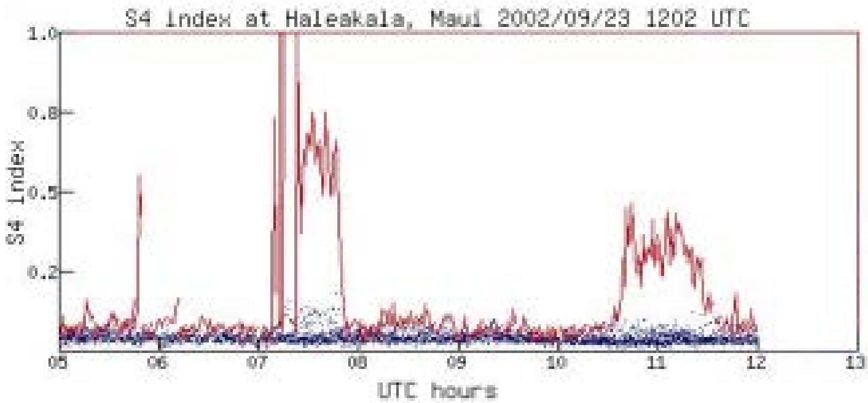

Figure 2. An example of S4 index data being accumulated from Hawaii. This example shows two minor events but with S4 values briefly reaching one. We show this event because it was convenient to download the image from the night previous to writing this report. More dramatic events are common.

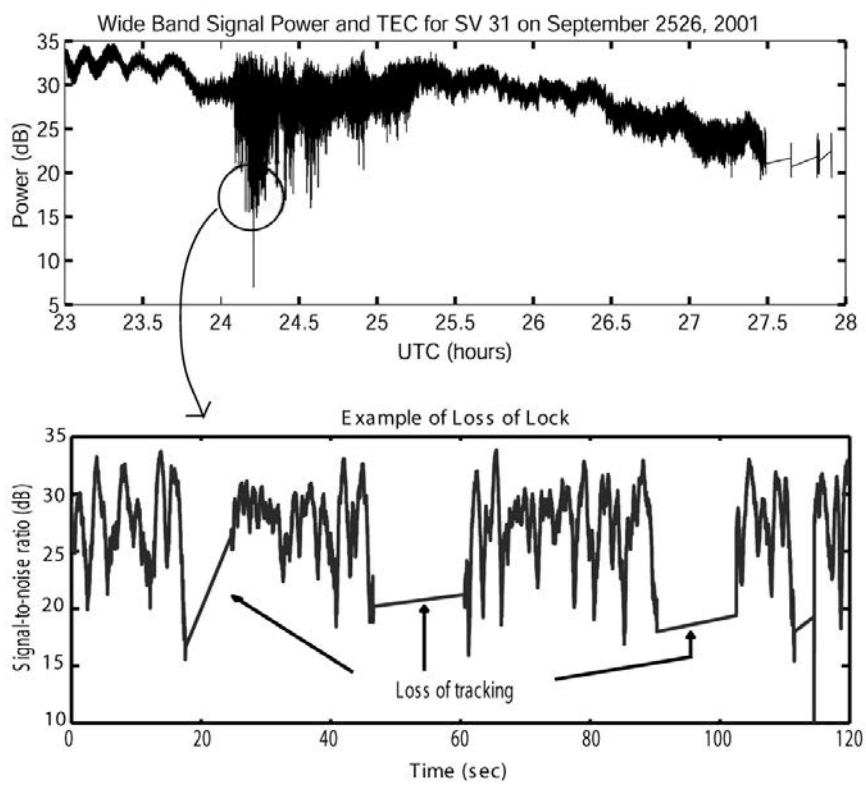

Figure 3. An example of GPS scintillations occurring at mid-latitudes (Ithaca, NY). The amplitude scintillations occurred during a minor magnetic storm (D_{st}=100 nt) and began at about 2400 UTC. The S4 index was nearly one and resulted in loss of tracking on several satellites. An example of loss of tracking is shown in the lower panel.

IMPACT/APPLICATIONS

Our work with GPS receivers and measurement of scintillations continues to be important in understanding and predicting the behavior of GPS receivers in the presence of scintillations. Determining the shape of fade patterns is important to understanding how velocity resonance will occur and potentially produce loss of lock or even loss of navigation in GPS receivers. The recent work on time scales is critical for determining the potential for airborne GPS receivers to have added sensitivity to GPS scintillations.

The expansion of our GPS scintillation program to mid-latitudes has been very fruitful. Not only have we been able to show that field lines mapping to well above the equatorial ionosphere produce spread-F disturbances in Hawaii but we have also demonstrated that substantial (S4=1) scintillations can occur in the northern United States.

TRANSITIONS

We are planning two major transitions in the next year. First, our "standard" GPS scintillation receiver needs redesigning to work on the now common PCI bus. This will facilitate our continued efforts toward developing a world-wide network and we will look for more collaborators willing to join us. Recently we demonstrated that a GPS signal simulator, purchased under DURIP funding, can simulate scintillations. With this result we will begin using measured scintillation activity to program the simulator and explore amplitude and temporal scales and their effect on GPS receiver reliability.

RELATED PROJECTS

Our NASA projects depend heavily on the funding of GPS receiver development. For example, the results from the ground-based GPS scintillation receivers were critical in determining goals for the LWS/Geospace Mission Definition Team report. The sounding rocket program at Cornell uses GPS receivers originally based on the scintillation receiver design.

The CUBEsat program, with which we are collaborating, uses a receiver based on the Cornell sounding rocket design and the GPS signal simulator, purchased with DURIP funding, is being used to develop and test the CUBEsat GPS receiver. In return we hope to make the first ever GPS amplitude scintillation measurements from orbit using the CUBEsat receiver.

We are co-Investigators on the electric field experiment for the ESA spacecraft Cluster. Nominal funding for data analysis should be received through Berkeley but their funds are insufficient for non-Berkeley co-investigator participation. To do this data analysis, we are combining funds from NSF and ONR to enable a graduate student to examine Cluster plasma wave data.

REFERENCES

Ledvina, B.M., J.J. Makela, and P.M. Kintner. (2002): First observations of GPS L1 amplitude scintillations at midlatitude, Geophys. Res. Lett., 29(14), 4-1 to 4-4, 10.1029/2002GL014770.

PUBLICATIONS

Beach, T.L., M.C. Kelley, P.M. Kintner and C.A. Miller. 1997: Total electron content variations due to nonclassical traveling ionospheric disturbances: Theory and Global Positioning System observations, J. Geophys. Res., 102(A4), 7279-7292.

Bonnell, J., P. Kintner, J.-E. Wahlund, and J.A. Holtet. 1997: Modulated Langmuir waves: Observations from Freja and SCIFER, J. Geophys. Res., 102(A8), 17,233-17,240.

Pinçon, J.L., P.M. Kintner, P.W. Schuck, and C.E. Seyler. 1997: Observation and analysis of lower hybrid solitary structures as rotating Eigenmodes, J. Geophys. Res., 102(A8), 17,283-17,296.

Kintner, P.M., R. Arnoldy, C. Pollock, T. Moore, J. Holtet, C. Deehr, and J. Moen. 1997: The SCIFER sounding rocket experiment, Proceedings 13th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Öland, Sweden, ESA SP-397.

Schuck, P.W., C.E. Seyler, J.-L. Pinçon, J.W. Bonnell, and P.M. Kintner. 1998: Theory, simulation, and observation of discrete eigenmodes associated with lower hybrid solitary structures, J. Geophys. Res., 103(A4), 6935-6953.

Franz, J.R., P.M. Kintner, and J.S. Pickett. 1998: POLAR observations of coherent electric field structures, Geophys. Res. Lett., 25(8), 1277-1280.

McAdams, K.L., J. LaBelle, P.W. Schuck, and P.M. Kintner. 1998: PHAZE II observations of lower hybrid burst structures occurring on density gradients, Geophys. Res. Lett., 25(16), 3091-3094, 1998.

Kintner, P.M. 1998: Plasma wave measurements: Skepticism and plausibility, in Measurement Techniques in Space Plasmas: Fields, AGU, Geophys. Mono. 103, 137-145.

Bonnell, J.W., P.W. Schuck, J.-L. Pinçon, C.E. Seyler, and P.M. Kintner. 1998: Observation of bound states and counterrotating lower hybrid eigenmodes in the auroral ionosphere, Phys. Rev. Lett., 80(26), 5734.

Wahlund, J.-E., A.I. Eriksson, B. Holback, M.H. Boehm, J. Bonnell, P.M. Kintner, C.E. Seyler, J.H. Clemmons, L. Eliasson, D.J. Knudsen, P. Norqvist, and L.J. Zanetti. 1998: Broadband ELF plasma emission during auroral energization, 1, Slow ion acoustic waves, J. Geophys. Res., 103(A3), 4343-4375.

Bhattacharyya, A., T.L. Beach, S. Basu, and P.M. Kintner. 1999: GPS studies of TEC variations and equatorial scintillations, Proceedings of IES99, JMG Associates LTD, 5A6-1 to 5A6-8.

Kintner, P.M., H. Kil, and E. De Paula. 1999: Fading time scales associated with GPS signals, Proceedings of IES99, JMG Associates LTD.

Aarons, J., M. Mendillo, B. Lin, M. Colerico, T. Beach, P. Kintner, J. Scali, B. Reinisch, G. Sales, and E. Kudeki. 1999: Equatorial F region irregularity morphology during an equinoctial month at solar minimum, Space Sci. Rev., 87, 357-386.

Beach, T.L., and P.M. Kintner. 1999: Simultaneous Global Positioning System observations of equatorial scintillations and total electron content fluctuations, J. Geophys. Res., 104(A10), 22,553-22,565.

Arnoldy, R.L., K.A. Lynch, J.B. Austin, and P.M. Kintner. 1999: Energy and pitch angle dispersed auroral electrons suggesting a time-variable, inverted-V potential structure, J. Geophys. Res., 104(A10), 22,613-22,621.

McAdams, K.L., J. LaBelle, M.L. Trimpi, P.M. Kintner, and R.A. Arnoldy. 1999: Rocket observations of banded structure in waves near the Langmuir frequency in the auroral ionosphere, J. Geophys. Res., 104(A12), 28,109-28,122.

Pickett, J.S., D.A. Gurnett, J.D. Menietti, M.J. LeDocq, J.D. Scudder, L.A. Frank, J.B. Sigwarth, K.L. Ackerson, D.D. Morgan, J.R. Franz, P.M. Kintner, B.T. Tsurutani, C.M. Ho, J. Chen, T.A. Fritz, C.T. Russell, W.K. Peterson, Y. Kasahara, I. Kimura, S. Watanabe, G.G. Arkos, G. Rostoker, S. Kokubum, H. Fukunishi, R.F. Pfaff, F.S. Mozer, S.-Y. Hsieh, T. Mukai, and M.O. Chandler. 1999: Plasma waves observed during cusp energetic particle events and their correlation with Polar and Akebono satellite and ground data, Adv. Space Res., 24(1), 23-33.

Psiaki, M.L., P.M. Kintner, Jr., and S.P. Powell. 2000: Rapid energy dissipation in a yo-yo-type wire boom deployment system, Journal of Guidance, Control, and Dynamics, 23(3), 483-490. (Also in Proceedings of the 1999 AIAA Guidance, Navigation, and Control Conf., Aug. 1999, Portland, OR, pp. 1424-1436.)

Psiaki, M.L., S.P. Powell, and P.M. Kintner, Jr. 2000: Accuracy of the Global Positioning System-derived acceleration vector, Journal of Guidance, Control, and Dynamics, 23(3), 532-538. (Also in Proceedings of the 1999 AIAA Guidance, Navigation, and Control Conf., Aug. 1999, Portland, OR, pp. 751-760.)

Bhattacharyya, A., T.L. Beach, S. Basu, and P.M. Kintner. 2000: Nighttime equatorial ionosphere: GPS scintillations and differential carrier phase fluctuations, Radio Sci., 35(1), 209-224.

Franz, J.R., P.M. Kintner, C.E. Seyler, J.S. Pickett, and J.D. Scudder. 2000: On the perpendicular scale of electron phase-space holes, Geophys. Res. Lett., 27(2), 169-172.

Kil, H., P.M. Kintner, E.R. de Paula and I.J. Kantor. 2000: GPS measurements of the ionospheric zonal apparent velocity at Cachoeira Paulista in Brazil, J. Geophys. Res., 105(A3), 5317-5238.

Kintner, P.M., P.W. Schuck, and J.R. Franz. 2000: Spaced measurements and progress in understanding space plasma waves, Phys. Plasmas, 7(5), 2135-2141.

Kintner, P.M., J. Franz, P. Schuck, and E. Klatt. 2000: Interferometric coherency determination of wavelength or What are BB-ELF waves?, J. Geophys. Res., 105(A9), 21,237-21,250.

Beach, T.L., and P.M. Kintner. 2001: Development and use of a GPS ionospheric scintillation monitor, IEEE Trans., 39(5), 918-928.

Kintner, P.M., H. Kil, and E. De Paula. 2001: Fading time scales associated with GPS signals and potential consequences, Radio Sci., 36(4), 731.

Beach, T.L., and P.M. Kintner. 2001: Development and use of a GPS ionospheric scintillation monitor, IEEE Trans. Geosci. Remote Sensing, 39(5), 918-928.

Hyosub, K., P.M. Kintner, E.R. de Paula, and I.J. Kantor. 2002: Latitudinal variations of scintillation activity and zonal plasma drifts in South America, Radio Sci., 37(1), 6-1 to 6-7, 10.1029/2001RS002468.

Kintner, P.M., H. Kil, C. Deehr, and P. Schuck. 2002: Simultaneous TEC and ASC measurements of an auroral arc, Radio Sci., in press.

Ledvina, B.M., J.J. Makela, and P.M. Kintner. 2002: First observations of GPS L1 amplitude scintillations at midlatitude, Geophys. Res. Lett., 29(14), 4-1 to 4-4, 10.1029/2002GL014770.